

## SUPPLEMENTARY DATA

### *Environmental resources*

The model uses monthly data obtained from conventional meteorological stations: overall mean ( $T_m$ ), mean maximum ( $T_{max}$ ) and mean minimum temperature ( $T_{min}$ ); precipitation ( $P$ ); potential evaporation ( $e_v$ ); global solar radiation ( $Q$ ); and wind speed ( $u$ ). Soil data are profile characteristics of horizons: depth, texture, bulk density, field capacity and wilting point.

Daytime ( $T_d$ ) and nighttime ( $T_n$ ) temperatures were computed from an empirical formula proposed by Norero (1995):

$$T_d = 0.47(T_{max} + T_{min}) + 0.22(T_{max} - T_{min}) \quad (1)$$

$$T_n = T_{max} + T_{min} - T_d \quad (2)$$

Available water for trees is based on a water balance budget (Norero, 1976). The output is the estimated real evapotranspiration ( $e_t$ ) and the maximum evapotranspiration ( $e_{tmax}$ ). The ratio  $e_t / e_{tmax}$  is a measure of the water deficit and is used as a restraining factor for growth: values close to 1 indicate adequate levels of water. The maximum value,  $e_{tmax}$ , is the product of the evaporative demand of the atmosphere ( $e_v$ ) and a plant factor,  $K_c$ , which varies as the vegetation grows and foliage expands (Doorenbos and Pruitt, 1984). To create a feed-back mechanism to compute  $e_{tmax}$  as the tree develops, the value of  $K_c$  is given as a ground cover factor of the stand computed as a function of the projected leaf area index ( $L_p$ ) or 1-sided leaf area index, equivalent to the leaf area index ( $L$ ) (or all-sided leaf area index) divided by  $\pi$  (Jarvis *et al.* 1976), thus:

$$e_{tmax} = e_v(1.1 - e^{(-KL_p)}) \quad (3)$$

With  $K$  the extinction coefficient of solar radiation based on Beer Lambert's law, assumed to be 0.5 (Jarvis *et al.*, 1976). Leaf area index is calculated as total leaf area in the tree (in  $m^2$ ), divided by ( $10,000 m^2/\text{number of trees ha}^{-1}$ ).

The sub-models of photosynthesis and respiration compute maximum rates of biomass production in time  $t$  ( $g_{\max}$ ) assuming optimal water availability. This value is modified by the water deficit restriction factor  $f_h$  and becomes the estimated real biomass production ( $g_{\text{real}}$ ):

$$g_{\text{real}} = f_h g_{\max} \quad (4)$$

The restraining function is (Norero, 1974):

$$f_h = g_{\text{real}}/g_{\max} = [(1+c) \times e_i/e_{t_{\max}} - c]^{c_v} \quad (5)$$

Coefficient  $c$  is a parameter for ground cover and rainfall interception of trees:

$$c = e^{(-KS_{II})} \quad (6)$$

$K$  is the extinction coefficient of solar radiation and  $S_{II}$  the total Surface Interception Index (corresponding to the the sum of all  $s_{ii}$  in the tree). The value of the exponent  $c_v$  in eqn 5 was estimated by Pedreros (2005) to be 1.05 for *P. radiata*, quite close to 1. A nutritional restraining factor ( $f_n$ ) similar to the water restriction factor is at present optional. In this case, the growth expression (eqn 7) will become the output of whichever function is in minimum relative supply, as, for instance, in the 3PG model (Landsberg and Waring, 1997).

$$g_{\text{real}} = g_{\max} \times \min\{f_h, f_n\} \quad (7)$$

The individual crown is an average crown of the whole stand, considering the stand as a homogeneous array of trees per ha. The crown is divided into  $k$  layers of equal width,

from the top of the tree to its base. All projected values are calculated considering the total leaf area ( $m^2$ ) (or total foliar area plus internode area,  $m^2$ ) of the simulated tree divided by ( $10,000 m^2 / \text{number of trees } ha^{-1}$ , corresponding to the ground area of one tree). Thus, individual values are representative average values for the stand, and stand density affects the interception of solar radiation.

Solar radiation incident on every productive growth unit F at a given  $k$  layer in the crown ( $q_k$ ) is equal to a fraction of the value at the top of the canopy ( $Q$ ). Part of the radiation incident on the trees reaches the ground and a fraction of this radiation is reflected back toward the canopy to become an additional, albeit small, input to leaves in layer  $k$ . Thus, total solar energy supply to any productive growth unit F in layer  $k$  is:

$$q_k = Q(1 - \alpha_p) e^{(-KS_{IIk})} + [Q(1 - \alpha_p) e^{(-KS_{IIk})}] \alpha_s e^{(-KS_{IIinvk})} \quad (8)$$

Parameters  $\alpha_p$  and  $\alpha_s$  are plant and soil albedo, respectively,  $K$  is the solar radiation extinction coefficient of the tree canopy,  $S_{IIk}$  is the cumulative Surface Interception Index from the top of the tree down to layer  $k$  or to the surface of the soil ( $S_{II}$ ), and  $S_{IIinvk}$  is the cumulative Surface Interception Index from the base of the tree up to  $k$ .

#### *Biosynthesis and biomass balance*

Photosynthetic rate is computed after the expression worked out by Norero (1983):

$$p_{hr} = [(1 - \beta)\theta - (r_x + r_i)c_f] / [(1 - \beta)(r_a + r_f + r_c + r_s + r_m) + r_x + r_i] \quad (9)$$

$p_{hr}$  is the net photosynthetic rate and includes daily foliage respiration ( $c_f$ );  $\beta$  is a coefficient of photorespiration (eqn 10);  $\theta$  is carbon dioxide concentration in the air;  $r_x$ ,  $r_i$ ,  $r_a$ ,  $r_f$ ,  $r_c$ ,  $r_s$  and  $r_m$  are resistances to the flux of carbon dioxide (Table 1).

With  $\beta$  as

$$\beta = (0.1q_k)/(1 + q_k)e^{[\ln(q_{10})/10T_d]} \quad (10)$$

With  $q_k$  the solar radiation incident upon the growth unit and  $q_{10}$  is the rate of increase of the respiratory activity when temperature is increased by 10 degrees °C.

Table 1: Resistances to carbon dioxide flux from atmosphere to photosynthetic sites.

Name	Equation	Units	Source
Aerodynamic resistance over the vegetative cover	$r_a=1.85 \cdot 10^{-4} \cdot \ln(15400/H-5.92) \cdot \ln(8700/H-3.35)$ (11)	[min cm <sup>-1</sup> ]	Pilatti and Norero, 2004
Interleaves aerodynamic resistance	$r_f=1.7 \cdot 10^{-4} \cdot \ln(15400/H-5.92)^2 \cdot \ln(19/[e^{(3 \cdot z/H)}-1])$ (12)	[min cm <sup>-1</sup> ]	Pilatti and Norero, 2004
Boundary layer resistance	$r_c=0.0166/(1.03+4.08 \cdot u_z)$ (13)	[min cm <sup>-1</sup> ]	Adapted from Jarvis <i>et al.</i> (1976)
Open stomate resistance $r_{s0}$	if $a \leq 42$ then $r_{s0}=0.0179 \cdot e^{(0.0447 \cdot a)}$ else $r_{s0}=0.14$ (14)	[min cm <sup>-1</sup> ]	Adapted from Ryan <i>et. al</i> (1996)
	Depending on foliage nitrogen content, which is related to the age of the foliage		
Partially open stomate resistance	$r_s=r_{s0}+6 \cdot 10^{-3} \cdot q_k^{-0.94}$ (15)	[min cm <sup>-1</sup> ]	Norero (1983)
Mesophyll resistance	$r_m=0.06$ (16)	[min cm <sup>-1</sup> ]	Norero (1983)
Carboxylation resistance	$r_x=0.0262/\gamma_e$ (17)	[min cm <sup>-1</sup> ]	Norero (1983)
Photolytic resistance	$r_i=0.0277/q_k$ (18)	[min cm <sup>-1</sup> ]	Norero (1983)

Total tree height is  $H$ . Function  $r_a$  assumes a wind speed of  $5 \text{ m s}^{-1}$  at 20 m high if wind data is not available;  $z$  is the height above ground level of the base of the internode under evaluation;  $u_z$  (eqn 19) is the wind speed at height  $z$  above the ground and is related to wind speed at 20 m high ( $u_{20}$ ),

$$u_z = u_{20} e^{[-3(1-z/H)]} \quad (19)$$

The resistance to carboxylation (Pilatti and Norero, 2004) includes the expression  $\gamma_e$  (eqn 20). This is a thermal function (Norero, 1987) that involves the effect of temperature upon enzymatic reactions involved in the capture of carbon dioxide molecules and their incorporation into organic metabolites:

$$\gamma_e = 1.227 \cdot \left( \frac{T_d - \varphi_{e \min}}{\varphi_e - \varphi_{e \min}} \right) \cdot \exp \left[ \frac{-0.0606}{\left( \frac{T_d - \varphi_{e \min}}{\varphi_e - \varphi_{e \min}} \right)} - 443.5 \cdot \left( \frac{T_d - \varphi_{e \min}}{\varphi_e - \varphi_{e \min}} \right) \cdot \exp \left( \frac{-8.03}{\left( \frac{T_d - \varphi_{e \min}}{\varphi_e - \varphi_{e \min}} \right)} \right) \right] \quad (20)$$

$\varphi_{e \min}$  is the minimum cardinal temperature and  $\varphi_e$  is the cardinal temperature for fastest enzymatic activity.

Finally, computation of net photosynthesis includes the leaf diurnal rate of respiration,  $c_f$ :

$$c_f = c_{f25} e^{[\ln(q_{10})/10(T_d - 25)]} \quad (21)$$

and

$$c_{f25} = r_b f_n (1/S_{LA}) \varepsilon \quad (22)$$

The parameter  $c_{f25}$  is a reference rate of respiration at 25 °C. The nitrogen content of live tissues has been shown to be an important indicator of biological activity. Norero (1995) advocated the concept of a basic respiration rate ( $r_b$ ) expressed in unit weight of CO<sub>2</sub> per unit weight of nitrogen and per hour at a temperature of 25 °C. He suggested that a typical value is  $r_b = 0.2 \text{ [g CO}_2 \text{ g N}^{-1} \text{ h}^{-1}]$ . Variable  $f_n$  is the nitrogen content of needles and depends on the age of the structure (Orman and Will, 1960, cited by

Uprichard, 1991; Ryan *et al.*, 1996). Based on the work of Ryan *et al.* (1996), a relation of the nitrogen content as a function of age was developed:

$$f_n = \left\{ \begin{array}{l} f_{n_0} \quad \text{for } a_{ge} \leq 6 \text{ months} \\ f_{n_0} \cdot [-9 \cdot 10^{-5} \cdot a_{ge}^2 - 0.0061 \cdot a_{ge} + 1.0308] \quad \text{for } 6 \text{ months} < a_{ge} \leq 48 \text{ months} \\ f_{n_0} \cdot [-9 \cdot 10^{-5} \cdot 48^2 - 0.0061 \cdot 48 + 1.0308] \quad \text{for } 48 < a_{ge} \end{array} \right\} \quad (23)$$

where  $f_{n_0}$  is the nitrogen content of 1-year-old needles. Implicit in this initial value of  $f_{n_0}$  is the nutritional condition of the tree;  $a_{ge}$  is the age of the internode and needles.

Then, overall net photosynthesis is:

$$p_h = p_{hr} S_{LAP} b_f d_{ay} d_n \quad (24)$$

The photosynthetic rate  $p_{hr}$  is multiplied by  $S_{LAP}$ , the Specific Leaf Area based on projected leaf area, and by leaf biomass  $b_f$  of the internode to yield the quantity of fixed  $CO_2$ . This value multiplied by day duration ( $d_{ay}$ , in  $\text{min d}^{-1}$ ), and by number of days per month,  $d_n$ , is the monthly net uptake of  $CO_2$  to be converted into new biomass.

The respiration sub model comprises the leaf night time respiration and the structural diurnal and nocturnal respiration (i.e., stems, branches and roots living tissue).

Night-time leaf respiration rate,  $c_{fn}$  is computed by eqn 25, with mean nocturnal temperature ( $T_n$ , eqn 2) as the driving variable:

$$c_{fn} = c_{f25} e^{[(\ln(q_{10})/10)(T_n - 25)]} \quad (25)$$

And total night-time leaf respiration per month ( $r_{fn}$ ) is:

$$r_{fn} = c_{fn} S_{LA} b_f d_{night} d_n \quad (26)$$

With  $S_{LA}$  Specific Leaf Area and  $d_{night}$  time duration of the night (in  $\text{min d}^{-1}$ ).

To evaluate the respiration rate of structural (woody) biomass at the level of F it is assumed that it is directly proportional to the leaf respiration rate as the ratio of their respective nitrogen contents. Based on data of Orman and Will (1960), a relation  $s_n/f_n = 0.22$  was derived between the nitrogen content of the wood ( $s_n$ ) in the internode and the needles of a given internode ( $f_n$ ). If the structure is deprived of leaves, the nitrogen content of a woody structure is considered to be the lowest reported value. In the trunk the ratio  $s_n/f_n$  is equal to 0.07.

Therefore, wood diurnal,  $c_b$ , and nocturnal respiration rate,  $c_{bn}$  are  $c_b = s_n/f_n c_f$  and

$$c_{bn} = s_n/f_n c_{fn}.$$

Monthly structural respiration during daylight time,  $r_{bd}$ , and night-time,  $r_{bn}$ , is computed multiplying  $c_b$  by the live woody biomass of F,  $b_a$ , the  $S_{LA}$ , the respective diurnal and nocturnal durations, and by the number of days per month, thus:

$$r_{bd} = c_b S_{LA} b_a d_{ay} d_n \quad (27)$$

$$r_{bn} = c_{bn} S_{LA} b_a d_{night} d_n \quad (28)$$

Then, total respiration per month of structural biomass plus foliar biomass at the internode level is:

$$r_{tot} = r_{fn} + r_{bd} + r_{bn} \quad (29)$$

Finally, the total monthly carbon balance at the internode level is the difference between net photosynthesis and total respiration, multiplied by the water stress restraining factor,  $f_h$  (eqn 5),

$$b_{al} = (p_h - r_{tot})f_h \quad (30)$$

Root respiration is computed assuming that roots have the same nitrogen content as order 1 leafless F units (eqn 23,  $a_{ge} > 48$  months) used to estimate  $c_{f25}$ ,  $c_f$  and  $c_{fn}$ . So, the diurnal respiration rate of roots is given by:

$$c_{root} = 0.07c_f \quad (31)$$

and the nocturnal respiration rate by:

$$c_{rootn} = 0.07c_{fn} \quad (32)$$

The daytime monthly root respiration is:

$$r_{rootd} = c_{root}B_rS_{LA}d_{ay}d_n \quad (33)$$

Variable  $B_r$  is live root biomass.

The night-time monthly root respiration is:

$$r_{rootn} = c_{rootn}B_rS_{LA}d_{night}d_n \quad (34)$$

Total root respiration per month is equal to the sum of diurnal and nocturnal respiration times a restriction factor due to water stress  $f_h$ :

$$r_{roott} = (r_{rootd} + r_{rootn})f_h \quad (35)$$

The total balance at the tree level,  $B_{AL}$ , in time  $t$ , is the sum of the balances of all internodes minus root respiration:

$$B_{AL} = \sum b_{al} - r_{roott} \quad (36)$$

Plants have metabolic reserves in storage tissues or organs. These reserves are used at the beginning of intensive growth periods or are mobilized when metabolic balance is



negative (Taiz and Zeiger, 2010). The model assumes the existence of a permanent reserve pool ( $R_{ES}$ ) proportional to the amount of live matter of the tree. This pool is recharged during periods of positive metabolic balance and is used to make up the balance in times of deficit. Details of this reserve charge sub-model are outlined in Fernández (2008).

When total tree balance  $B_{ALt}$  is negative, the tree does not keep its normal respiration rate. In this case a Compensation Sub-model comes into operation and either (a) delivers reserves to the system or else, if reserves of time  $(t - 1)$  ( $R_{ES(t-1)}$ ) are not enough to counteract a negative balance, (b) it eliminates branches until the balance is restored to a zero value. The system removes certain structures ( $E_t$ ) such that the negative balance plus reserves of time  $(t-1)$  is equal to zero:

$$\text{if } B_{ALt} < 0 \text{ and } R_{ES(t-1)} + B_{ALt} < 0 \text{ then } E_t = |R_{ES(t-1)} + B_{ALt}| \quad (37)$$

Elimination of structures proceeds as follows: (a) in a subsystem axis of order 4 are eliminated first, then order 3, order 2 and, if necessary, order 1 (death of the whole tree); (b) subsystems with negative balance  $B_{al} < 0$ , that also exceed a certain minimum age limit ( $a_{lim}$ , parameter) are eliminated; (c) older subsystems with larger negative balances are eliminated first.

Condition (b) forces the tree system to eliminate branch subsystems that become a burden to the whole system. By setting a minimum age limit, elimination of new or young branches with negative balances is avoided, inasmuch as their negative balance might be the result of a normal juvenile development, rather than a consequence of a true unproductive condition. Condition (c) lends priority to the elimination of branch subsystems growing closer to the base of the supporting branch.

The elimination protocol ends when the overall sum of negative balance of subsystems equals  $E_i$ ; and the new  $B_{ALi} = 0$ . Every time a unit F and its tributaries are eliminated, a certain amount of biomass to be eliminated is redistributed (translocated) into the system as variable  $T_{RASi}$  and is available for the next balance. The proportion of biomass to be traslocated ( $\alpha_T$ ) was defined after Norero (pers. comm.). When branches disappear an equivalent amount of roots is eliminated, in accordance to the principle of a conservative shoot–root ratio.

*Phyllotaxis and size relationship of branches in a cluster.*

Example of transition Matrix for first order Markov chain of probability of branches vigour in a cluster of  $n = 6$  lateral structures:

n=6	0.20	0.40	0.60	0.80	1.00
0.20	1.00	0.00	0.00	0.00	0.00
0.40	0.35	0.65	0.00	0.00	0.00
0.60	0.06	0.45	0.49	0.00	0.00
0.80	0.03	0.11	0.39	0.47	0.00
1.00	0.00	0.03	0.10	0.34	0.53

*Turnover of needles*

Coefficients values of the logistic function that describes the probability of the needles to be alive or not in a given internode, depending on its position in the crown and internode's age.

Table 3: Coefficients for needles death prediction

Order	Sample for estimation ( $n$ )	Intercept $\mu_1$	Var: $a_{ge}$ $\mu_2$	Var: ( ${}^H_{tree} - {}^H_{Fi}$ ) $\mu_3$	Percentage of successful prediction
1	729	7.8602	-0.0891	-0.0159	93%
2	347	5.6420	-0.0807	-0.0018	78%
3	1467	10.6172	-0.1091	-0.0051	95%
4	200	8.8290	-0.1857	-0.0007	89.5%

$a_{ge}$  (months): internode age at time  $t$   
 $({}^H_{tree} - {}^H_{Fi})$  depth within the crown (cm)